RECOGNITION OF LOWER LIMB MOVEMENTS BY ARTIFICIAL NEURAL NETWORK FOR RESTORING GAIT OF HEMIPLEGIC PATIENTS BY FUNCTIONAL ELECTRICAL STIMULATION

T.Watanabe[1, 2], S.Yamagishi[2], H.Murakami[3], N.Furuse[4], N.Hoshimiya[2] and Y.Handa[5]

[1]Information Synergy Center, Tohoku University, Sendai, Japan
[2]Graduate School of Engineering, Tohoku University, Sendai, Japan
[3]Niigata Institute of Technology, Kashiwazaki, Japan
[4]Miyagi National College of Technology, Natori, Japan
[5]New Industry Creation Hatchery Center, Tohoku University, Sendai, Japan

Abstract-**This study focused on man-machine interface of FES system for restoring gait of hemiplegic patients. A method of recognition of lower limb movements using an artificial neural network (ANN) was examined in monitoring restored motions and in giving control command with normal subjects and a hemiplegic patient. Acceleration signals were measured with a three-axis accelerometer attached to the heel of the normal side (right side) during walking for using in the recognition. Subjects performed some specific movements by their normal lower limbs supposing control command input in the walking measurements. The ANN recognized three different walking patterns, which were level floor walking, going up and down stairs, based on the acceleration waveforms with about 80% of recognition rate for normal subjects and above 70% for the patient. A similar structure of the ANN discriminated four specific movements by the lower extremity with more than 90% of recognition rate after the third performance of the movement simulated by using recognition and mis-recognition rates for experimentally measured data. The method was found to be useful in monitoring FES movements for safety and in giving control commands to the FES system without using upper limbs.**
Keywords - **FES, neural network, gait, hemiplegics**

I. INTRODUCTION

Walking of hemiplegic patients on level floor has been improved by controlling ankle dorsiflexion using functional electrical stimulation (FES). The main purpose of this method is to correct the drop foot during walking. The method usually uses foot switches to detect the toe off and the heal contact of the paralyzed foot. Electrical stimulus pulse train is applied to muscles, mainly the tibialis anterior, on the basis of predetermined stimulation data during the swing phase detected by the foot switches.

It is required to make secure the patient's safety during FES gate for practical use. From this point of view, monitoring restored motions can be an important function of FES system in addition to feedback control. Although non-restraint measurement of walking [1] and detection of gait phase [2] have been studied, detection of walking pattern at every step has not been realized.

For going up and down stairs freely in addition to level floor walking, it is necessary to control a lot of muscles relating to the ankle, the knee and the hip joints using appropriate stimulation data to restore different walking patterns. That is, a lot of control commands are required to restore many movements. In restoring motor functions of lower extremity, a patient also uses usually crutch, cane, stick and so on. In this case it is not desirable to use upper extremities for giving control commands because of assuring the safety of patients. Alternatives to using upper extremities for the command input may be to use head, shoulder or lower limb of the normal side.

We have shown that an artificial neural network (ANN) had the ability to recognize a specific movement measured with the three-dimensional position sensor [3]. Using this technique, we focused on developing man-machine interface of FES system for monitoring restored motions and giving control commands. In this paper, the ability of an ANN was examined in recognition of walking patterns based on acceleration waveforms measured with a 3-axis accelerometer during walking on the level floor, going up and down stairs with neurologically intact subjects and a hemiplegic patient. The ability of recognition of some specific movements for giving control commands was also examined using the similar structure of the ANN.

II. METHODOLOGY

A. Measurement of lower movements of the normal side

Subjects were 5 neurologically intact male (22-24yrs.) and a hemiplegic patient (female, 55yrs.). Three-axis accelerometer (8692C50M1, KISTLER) was attached to the heel of the shoe of normal side (Fig.1). The right side was assumed to be the normal side in the case of normal subjects. Foot-switches were attached on the heel and the thumb pad of the foot of the normal side in order to detect the stance and the swing phases for ANN learning. Both acceleration and foot-switch data were recorded with data recorder (RD-135T, TEAC). These data were low pass filtered (f_c=20Hz) and sampled at 200Hz into personal computer after measurement.

Walking patterns for measurement were i) straight walking on the level floor, ii) going up stairs and iii) going down stairs. In each walking measurement, subjects performed specific movements by their normal side for supposed control command input at 1) the start of level floor walking, 2) the start of going up stairs, 3) the start of going down stairs and 4) the stop of walking. Specific movements were #1) knee flexion for command 1), #2) upward movement of the knee for command 2), #3) inner rotation of the lower thigh with toe contact for command 3) and #4) plantar-flexion of the ankle with toe contact for command 4).

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Abstract

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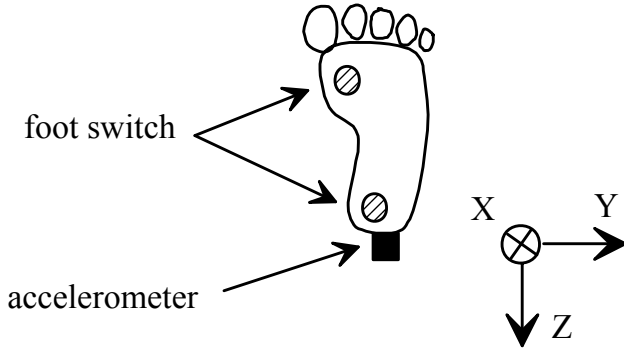
Fig.1 Arrangement of an accelerometer and foot switches for the right foot. Directions of the 3-axis accelerometer are shown in the figure.

Fig.2 Structure of the artificial neural network (ANN) used for recognition of walking patterns. The value of n was 20.

The first step was made by the normal side in the level floor walking and going up stairs. In the case of going down stairs, the paralyzed side made the first step. The hemiplegic patient used the stick during level floor walking and the grab rail during stair walking. There is no other restriction for subjects during walking. The numbers of measurements were 10 for three walking patterns with normal subjects, 10 for level floor walking and 5 for stair walking patterns with the patient. In the case of stair walking of normal subjects, one or two steps of the normal side on the level floor were included before and after the stair walking. In order to lightening a burden on the patient for the measurement, we instructed her to stop stair walking halfway.

B. Recognition of walking patterns for monitoring

Level floor walking, going up and going down stairs were recognized by the three-layer feed-forward style ANN shown in Fig.2. The numbers of neurons were 60 for the input layer, 10 for the hidden layer and 3 for the output layer. Measured acceleration signals were low pass filtered (f_c=3Hz) and sampled at 20Hz for the input to neurons of the input layer. The number of the neuron of the input layer was 60 (20 for each component) because the swing phase was about 1s. Changes of the acceleration signal from the amplitude of 1~ 20 samples before were given to each neuron of the input layer for the period of 1s before the recognition (see Fig.2). Each neuron of the output layer outputs the recognition result of level floor walking, going up or going down stairs, respectively.

Error back propagation algorithm was used for learning of the ANN. Teacher signal HIGH (numerical value was 0.99) was applied at the end of the swing phase detected by the foot switches i) between the second step and the step before the stop for level floor walking, ii) between the second step from the bottom of stairs and the top step for going up stairs and iii) between the second step from the top and the first step on level floor just after the stair walking for going down stairs. Teacher signal LOW (numerical value was 0.01) was given at other time. Amounts of adjustment of connection weights were 5 times of the calculated value at when teacher signal was HIGH (0.99), while those at when teacher signal was LOW (0.0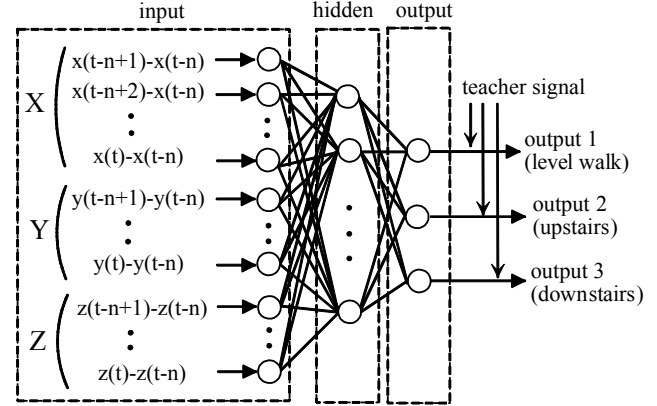1) were the calculated values. The adjustments were accumulated and added to connection weights after all the learning data were given. The adjustment of weights was repeated until the squared error function was less than reference value. The maximum repetition number of the learning was 40,000. Learning coefficient was 0.02. Initial value of coefficient of the inertia term was 0, the increment of the coefficient was 0.01 and the maximum was 0.9.

Each neuron of the output layer made numerical value between 0 and 1.0 using sigmoidal function. The output value that was larger than or equal to 0.5 meant that the neuron detected the movement. When detection results of all output neurons were correct, the ANN made correct recognition.

C. Recognition of specific movements for control commands

A method of recognizing specific movements was studied for using in control command input. Structure of the ANN used in specific movement recognition was similar to the ANN for walking pattern recognition. The difference was the number of neurons in the output layer. Four neurons were used in the output layer for specific movement recognition. Each neuron detected each movement described in section II A. Signal conditioning for the input to the ANN was the same as for the ANN for walking pattern recognition.

Two measured data for each walking were used for the ANN learning. Acceleration signals during movement #2 and #3 in the learning data were copied and added to the end of the learning data three times. Teacher signal HIGH (numerical value was 0.99) was applied at the end of specific movement and LOW (numerical value was 0.01) was applied at other time. The other parts of learning method were the same as that for walking pattern recognition. Output value also had same meaning as that of walking pattern recognition.

III. RESULTS

An example of measured acceleration signal during level floor walking is shown in Fig.3. The subject performed specific movements at the beginning of walking (movement #1) and just after the final step of walking (movement #4) in this walking. From the second step of the normal side to the step before the final one were used for the learning and the

recognition.

A. Recognition of walking patterns

Recognition rate was defined as the ratio of the number of correct recognition to the total number of steps and movements for recognition [%]. Recognition rates to unlearned data (7 measured data for normal subjects, 3 data for the patient) are shown in Table 1. Mean recognition rates were about 80% for normal subjects and about more than 70% for the patient.

With the 6 subjects including the patient, the mis-recognitions that output numerical value was less than 0.5 and that different movement was detected at when teacher signal was HIGH (0.99) were 61.1% and 2.6% of total

(c)

number of mis-recognition for level floor walking, 61.5% and 3.7% for going up stairs and 67.2% and 6.0% for going down stairs, respectively. The other mis-recognition (36.4% of total number of mis-recognition for level floor walking, 34.8% for going up stairs and 26.8% for going down stairs) was the case of the output numerical value was larger than or equal to 0.5 at when teacher signal was LOW (0.01).

B. Recognition of specific movements

Table 2 shows the recognition results of specific movements for unlearned data. The recognition rate was defined as the ratio of the number of correct recognition to the total number of performed movement. The numbers of unlearned data were 24 for normal subjects and 14 for the patient.

Recognition rate to four specific movements was over 70% for normal subjects. Most of mis-recognitions were

Table 2 Recognition results of specific movements to unlearned data [%]. The numbers of performed specific movements were 40 for movement #1, 8 for #2 and #3, and 24 for #4 in the case of normal subject. In the case of the patient, those were 8, 3, 3, and 8 for each movement, respectively. The numbers of movements and steps at when teacher signal was LOW were 264 for normal subjects and 109 for the patient. For mis-recognition, the ratio of it to the total number of movements and steps is shown.

teacher signal	correct recognition						mis-recognition		
	HIGH					LOW	HIGH	HIGH	LOW
output value	$0.5\leq$					< 0.5	< 0.5	other movements detected	$0.5\leq$
	#1	#2	#3	#4	mean				
normal A	82.5	75.0	62.5	50.0	70.0	100.0	20.0	10.0	0.0
B	92.5	75.0	75.0	91.7	88.8	100.0	5.0	6.3	0.0
C	70.0	87.5	87.5	70.8	73.8	99.2	21.3	5.0	0.76
D	80.0	75.0	50.0	70.8	73.8	96.6	25.0	1.3	3.4
E	75.0	75.0	100.0	75.0	77.5	99.2	16.3	6.3	0.76
mean	80.0	77.5	75.0	71.6	76.8	99.0	17.5	5.78	0.98
patient	25.0	0	0	87.5	41.0	96.3	31.8	27.3	3.7

movement and a step. It was 66.0% of the total number of mis-recognition in average for the normal subjects. Mis-recognition caused by detecting a different movement at when teacher signal was HIGH (0.99) and detecting a movement at when teacher signal was LOW (0.01) were 21.7% and 12.3% of the total number of mis-recognition in average for the normal subjects, respectively.

Supposing re-input of control command in the case of output value of the ANN was less than 0.5 when a specific movement was performed, recognition rates P_1, P_2 and P_3 were calculated by following equations:

$$P_1 = s \qquad \text{: first movement}$$
$$P_2 = s+rs \qquad \text{: second movement}$$
$$P_3 = s+rs+r^2s \qquad \text{: third movement}$$

where s is the recognition rate for the first movement. Mean recognition rate of the four movements was used as the value of s for each subject. The value of r is the rate of the number of mis-recognition, which was caused by low output value (less than 0.5) at when teacher signal was HIGH (0.99), to the total number of recognition. Results are shown in Table 3. After the supposed third input of control command, the system was expected to provide 92.4% of recognition rate in average with normal subjects.

IV. DISCUSSION

In walking pattern recognition, most of the mis-recognition at when teacher signal was LOW (0.01) was caused by specific movements. The ANN mis-recognized specific movements for giving control command as one of three walking patterns. Especially, movement #2 for the start of going up stairs was incorrectly recognized as walking pattern of going up stairs. Therefore, performing specific movements clearly is expected to decrease the mis-recognition rate. In the case of normal subjects, it is possible to obtain higher recognition rate for specific movements than those of experimental results by performing the movements more clearly. Selecting specific movements, which is different from walking patterns, also can be a solution for decreasing the mis-recognition.

However, variation of acceleration pattern during walking was sometimes observed in recorded signals causing low recognition rate, e.g. in the case of level floor walking with subject B and going down stairs with subject E. Variation of walking speed also made difference in acceleration pattern between measurements. Mis-recognition caused by variation of acceleration pattern in the same walking has to be solved for practical application.

For specific movement recognition, the average recognition rate after the supposed third command input was high (more then 90%) with the normal subjects. This shows that the method can be practical. In the case of the patient, however, the rate was low. A possible reason for the low rate was the difficulty of performing specific movements by the normal side with the support of the paralyzed side. Even if it was the reason, high recognition rate for the movement #4 was obtained (Table 2). The movement #4 was plantar-flexion of the ankle with toe contact. The toe contact of the

Table 3 Measured (P_1) and simulated (P_2 and P_3) mean recognition rates for specific movements [%]. P_1 is the measured ratio. P_2 and P_3 mean simulated rates for supposed second and third movement, respectively.

subject	P_1	P_2	P_3
normal A	70.0	84.0	86.8
B	88.8	93.2	93.4
C	73.8	89.4	92.8
D	73.8	92.2	96.8
E	77.5	90.1	92.1
mean	76.8	89.8	92.4
patient	41.0	54.1	58.3

normal side is considered to improve the stability during performing specific movements by the normal side. This indicates that selecting movements carefully is necessary to obtain high recognition rate.

V. CONCLUSION

This study examined the use of ANN for recognition of walking patterns and specific movements. Movements were measured with a three-axis accelerometer attached to the heel of shoe of the normal side. The technique was found to be useful for monitoring walking and giving control command. The technique is expected to provide information for assuring the safety of patients and to improve operationality of the FES system for practical use.

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